Supporting information

Population dynamics of free-roaming dogs and implications for population control

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1. Details of study regions, study sites and historical dog population management

Pescara is located in southern Italy in the Abruzzo region and has an oceanic climate (Peel, Finlayson, & Mcmahon, 2007). The province has a total area of 1,230km^2 and a population size of 318,909 ("Istituto Nazionale Di Statistica," n.d.). Population density is 123 people per km^2 (State Statistics Service of Ukraine, n.d.). Lviv is located in the west of Ukraine and has a temperate continental climate (Peel et al., 2007). The region covers 21,833km^2 and the population size is 2,522,021 (State Statistics Service of Ukraine, 2018). The population density is 115 people per km^2 across the region. Study regions were selected where networks were established to facilitate data collection, including sites where there was existing historical information on dog population management. In Pescara, this network was the Veterinary

Services – Pescara Province Local Health Unit, an organisation involved in dog population management. In Lviv, these networks were VIER PFOTEN International, the Lviv local Communal Enterprise, and Animal-id.info. Both VIER PFOTEN International and the Lviv local Communal Enterprise have been involved in dog population management in Lviv.

Prior to the fieldwork commencing, pilot trips to the study sites were conducted to check the suitability of the selected study sites for: (i) accessibility (i.e., no private land such as industrial areas where access is prohibited); and (ii) the presence of free-roaming dogs. Data collected during the pilot trip was not included in the analysis. The study sites remain anonymous as a condition of data sharing with the local networks.

Table S1. Numbers of dogs caught, neutered and released to study sites in Pescara, Italy and Lviv, Ukraine between 2014 and 2019. Sources: Veterinary Services – Pescara Province Local Health Unit for Pescara; and local Communal Enterprise for Lviv.

		Number of dogs released to study site						
	Study site	**2014**	**2015**	**2016**	**2017**	**2018**	**2019 (Jan-Jul)**	**Total**
Pescara	One	5	11	7	13	4	4	44
	Two	4	8	6	10	6	3	37
	Three	3	8	6	3	4	10	34
	Four	14	10	22	4	9	5	64
Lviv	One	0	0	69	105	89	7	270
	Two	0	0	34	58	51	20	163
	Three	0	0	0	0	0	0	0
	Four	0	0	1	0	0	0	1

2. Survey details, timings and weather

Survey routes were designed to maximise street coverage across the study site and avoid enclosed areas as a safety measure to reduce the risk of dog attack. Roads without a pavement were excluded as a traffic safety measure. The street surveys followed the same route across both the secondary and primary sampling days. Although this did not occur during this study, surveys were to be terminated for any days that may show abnormal free-roaming dog numbers, for example due to unusual weather (e.g. extremely high or low temperature or prolonged heavy rain).

All surveys took place between 06:00 and 10:00. In Ukraine, out of 60 surveys, 58 (97%) surveys took place between 06:30 and 09:30, one survey (2%) was missed due to illness, and one survey (2%) began at 06:00 due to logistical constraints. In Italy, out of the 60 surveys, 59 (98%) took place between 06:30 and 09:30, and one survey began at 06:00 due to logistical constraints. For the survey that was missed due to illness, NA's were included in the array of capture histories ($\gamma^{(i \times t \times s)}$) for study site one in Lviv for primary period three, secondary sampling period two. For the predictor variables, temperature and rainfall (no rainfall) was recorded using records in weather.com, the missed survey day was a weekday and market event was recorded as NA.

Table S2. Survey timings, distance and length (minimum, maximum and mean) in study sites in Pescara, Italy and Lviv, Ukraine.

Study region	**Study site**	**Distance (km)**	**Survey time (minutes)**			**Start time**			**End time**		
			Min	**Max**	**Mean**	**Min**	**Max**	**Mean**	**Min**	**Max**	**Mean**
Pescara	One	3.38	49	97	63	06:53	07:08	06:59	07:44	08:30	08:01
	Two	6.20	49	81	67	06:55	07:09	07:00	07:49	08:17	08:07
	Three	8.79	76	128	92	06:52	07:15	07:01	08:16	09:00	08:33
	Four	6.50	77	106	87	06:00*	07:21	06:57	07:18	08:45	08:24
Lviv	One	8.44	77	153	99	06:50	07:13**	07:00	08:14	08:57	08:32
	Two	7.20	86	112	95	06:45	07:30**	07:01	08:13	09:01	08:36
	Three	9.43	74	121	101	05:58*	07:40**	07:01	07:53	09:14	08:48
	Four	7.64	86	135	107	06:50	07:31**	07:05	08:26	09:27	08:51

* Survey began earlier due to logistical constraints.

** Survey began later due to daylight hours (sunrise at later time).

Table S3. Primary and secondary sampling period timings, temperature and weather conditions in Pescara, Italy.

Primary sampling period	Study site	Secondary sampling period	Date	Start Temp	Finish Temp	Mean temperature (ºC)	Rain	Market event	Start time	Finish time	Survey length (minutes)
One (April 2018)	One	1	11/04/2018	11	11	11	Yes	No	07:00	07:57	57
		2	12/04/2018	13	13	13	No	No	07:00	08:01	61
		3	13/04/2018	11	12	11.5	No	No	06:53	08:30	97
	Two	1	14/04/2018	11	12	11.5	No	No	06:55	08:16	81
		2	15/04/2018	13	13	13	No	No	06:55	08:16	81
		3	16/04/2018	14	14	14	No	No	07:00	08:09	69
	Three	1	17/04/2018	12	13	12.5	No	No	06:52	08:26	94
		2	18/04/2018	14	14	14	No	No	06:58	08:42	105
		3	19/04/2018	13	16	14.5	No	No	06:52	09:00	128
	Four	1	20/04/2018	14	17	15.5	No	No	06:55	08:41	106
		2	21/04/2018	14	14	14	No	No	06:49	08:23	94
		3	22/04/2018	12	14	13	No	No	06:50	08:16	86
Two (July 2018)	One	1	06/07/2018	22	23	22.5	No	No	06:55	08:03	68
		2	07/07/2018	20	22	21	No	No	07:00	08:20	80
		3	08/07/2018	20	22	21	No	No	06:55	08:10	75
	Two	1	09/07/2018	21	24	22.5	No	No	07:03	08:10	67
		2	10/07/2018	19	22	20.5	No	No	06:55	08:12	77
		3	11/07/2018	24	24	24	No	No	07:00	08:00	60
	Three	1	12/07/2018	20	23	21.5	No	No	07:09	08:57	108

Primary sampling period	Study site	Secondary sampling period	Date	Start Temp	Finish Temp	Mean temperature (ºC)	Rain	Market event	Start time	Finish time	Survey length (minutes)
		2	13/07/2018	22	24	23	No	No	07:00	08:34	94
		3	14/07/2018	21	24	22.5	No	Yes	07:06	08:36	90
	Four	1	15/07/2018	23	26	24.5	No	No	07:05	08:39	94
		2	16/07/2018	23	26	24.5	No	No	07:05	08:33	88
		3	17/07/2018	19	19	19	Yes	No	07:01	08:20	79
Three (October 2018)	One	1	02/10/2018	12	13	12.5	No	No	07:00	08:00	60
		2	03/10/2018	12	13	12.5	No	No	07:00	08:00	60
		3	04/10/2018	13	14	13.5	No	No	06:55	08:02	67
	Two	1	05/10/2018	16	15	15.5	Yes	Yes	07:06	08:09	63
		2	06/10/2018	14	16	15	Yes	No	07:01	08:17	76
		3	07/10/2018	14	16	15	No	No	06:58	08:10	72
	Three	1	08/10/2018	13	14.5	13.75	No	No	07:00	08:32	92
		2	09/10/2018	14	15	14.5	No	No	07:02	08:34	92
		3	10/10/2018	14	15	14.5	No	No	07:15	08:45	90
	Four	1	11/10/2018	14	16	15	No	No	07:15	08:45	90
		2	12/10/2018	17	17	17	No	No	06:56	08:22	86
		3	13/10/2018	13	14	13.5	No	No	07:21	08:43	82
Four (April 2019)	One	1	07/04/2019	8	9	8.5	Yes	No	07:00	07:51	51
		2	08/04/2019	10	9	9.5	No	No	07:08	08:04	56
		3	09/04/2019	12	12	12	No	No	06:55	07:44	49
	Two	1	10/04/2019	9	10	9.5	No	No	07:00	08:03	63

Primary sampling period	Study site	Secondary sampling period	Date	Start Temp	Finish Temp	Mean temperature (ºC)	Rain	Market event	Start time	Finish time	Survey length (minutes)
		2	11/04/2019	7	9	8	No	No	07:09	08:07	58
		3	12/04/2019	7	9	8	No	No	07:00	07:49	49
	Three	1	13/04/2019	7	7	7	No	Yes	07:00	08:23	83
		2	14/04/2019	7	8	7.5	No	No	07:00	08:23	83
		3	15/04/2019	7	7	7	Yes	No	07:00	08:22	82
	Four	1	16/04/2019	9	10	9.5	No	No	07:00	08:20	80
		2	17/04/2019	9	12	10.5	No	Yes	07:00	08:23	83
		3	18/04/2019	11	12	11.5	No	No	07:00	08:44	104
Five (July 2019)	One	1	09/07/2019	25	26	25.5	No	No	07:05	08:04	59
		2	10/07/2019	23	23	23	No	No	07:00	07:52	52
		3	11/07/2019	19	21	20	No	Yes	07:00	07:50	50
	Two	1	12/07/2019	19	22	20.5	No	Yes	06:57	08:06	69
		2	13/07/2019	20	22	21	No	No	07:03	08:00	57
		3	14/07/2019	18	19	18.5	No	No	07:05	08:02	57
	Three	1	15/07/2019	17	19	18	No	No	07:14	08:33	79
		2	16/07/2019	17	18	17.5	No	No	07:00	08:16	76
		3	17/07/2019	17	19	18	No	No	07:01	08:26	85
	Four	1	18/07/2019	18	22	20	No	No	07:00	08:20	80
		2	19/07/2019	19	21	20	No	No	07:00	08:17	77
		3	20/07/2019	19	22	20.5	No	No	06:00	07:18	78

Table S4. Primary and secondary sampling period timings, temperature and weather conditions in Lviv, Ukraine.

Primary sampling period	Study site	Secondary sampling period	Date	Start Temp	Finish Temp	Mean Temperature (ºC)	Rain	Market event	Start time	Finish time	Survey length (minutes)
One (April 2018)	One	1	01/05/2018	12	19	15.5	No	No	07:00	08:57	117
		2	02/05/2018	11	17	14	No	No	06:55	08:53	118
		3	03/05/2018	14	17	15.5	No	No	06:50	08:29	99
	Two	1	04/05/2018	10	17	13.5	No	No	06:50	08:42	112
		2	05/05/2018	13	14	13.5	No	No	06:45	08:21	96
		3	06/05/2018	11	11	11	No	No	06:45	08:13	88
	Three	1	07/05/2018	6	24	15	No	No	06:55	08:55	120
		2	08/05/2018	11	13	12	No	No	06:55	08:50	115
		3	09/05/2018	14	17	15.5	No	No	06:50	08:45	85
	Four	1	10/05/2018	12	17	14.5	No	No	06:55	08:50	115
		2	11/05/2018	10	16	13	No	No	06:55	08:26	91
		3	12/05/2018	9	13	11	No	No	06:50	08:34	104
Two (July 2018)	One	1	20/07/2018	18	19	18.5	No	No	07:00	08:28	88
		2	21/07/2018	17	19	18	No	Yes	07:00	08:47	107
		3	22/07/2018	14	18	16	No	No	07:00	08:24	84
	Two	1	23/07/2018	18	19	18.5	No	No	07:00	08:41	101
		2	24/07/2018	18	19	18.5	Yes	No	07:00	08:36	96
		3	25/07/2018	18	18	18	No	No	07:00	08:42	102
	Three	1	30/07/2018	17	21	19	No	No	07:00	09:14	74
		2	31/07/2018	18	19	18.5	Yes	No	07:00	08:48	108

Primary sampling period	Study site	Secondary sampling period	Date	Start Temp	Finish Temp	Mean Temperature (ºC)	Rain	Market event	Start time	Finish time	Survey length (minutes)
		3	01/08/2018	18	19	18.5	No	No	05:58	07:53	115
	Four	1	27/07/2018	17	21	19	No	No	06:50	09:05	135
		2	28/07/2018	17	21	19	No	No	06:55	08:58	124
		3	29/07/2018	20	21	20.5	No	No	07:00	09:07	127
Three (October 2018)	One	1	16/10/2018	6	7	6.5	No	No	06:55	08:28	94
		2	17/10/2018*	5	7	6	NA	NA	NA	NA	NA
		3	18/10/2018	7	7	7	No	No	07:13	08:46	153
	Two	1	19/10/2018	7	9	8	No	No	07:20	08:50	90
		2	20/10/2018	8	9	8.5	No	No	07:30	09:01	91
		3	21/10/2018	7	7	7	Yes	No	07:28	09:00	92
	Three	1	22/10/2018	0	1	0.5	No	No	07:27	09:07	100
		2	23/10/2018	6	6	6	Yes	No	07:30	09:07	97
		3	24/10/2018	6	6	6	Yes	No	07:40	09:11	91
	Four	1	25/10/2018	3	3	3	No	No	07:31	09:27	122
		2	26/10/2018	6	6	6	No	No	07:30	09:08	98
		3	27/10/2018	8	8	8	No	Yes	07:30	09:13	103
Four (April 2019)	One	1	26/04/2019	9	15	12	No	Yes	07:00	08:36	94
		2	27/04/2019	16	17	16.5	No	No	07:00	08:25	85
		3	28/04/2019	12	12	12	No	No	06:57	08:14	77
	Two	1	29/04/2019	9	10	9.5	Yes	No	07:00	08:26	86
		2	30/04/2019	9	10	9.5	Yes	No	06:50	08:21	91
		3	01/05/2019	8	8	8	Yes	No	06:55	08:24	89

Primary sampling period	Study site	Secondary sampling period	Date	Start Temp	Finish Temp	Mean Temperature (ºC)	Rain	Market event	Start time	Finish time	Survey length (minutes)
	Three	1	02/05/2019	7	10	8.5	No	No	06:57	08:58	121
		2	03/05/2019	9	12	10.5	No	No	07:08	08:50	102
		3	04/05/2019	8	8	8	No	No	07:02	08:49	107
	Four	1	05/05/2019	9	9	9	Yes	No	07:06	08:49	103
		2	06/05/2019	5	5	5	Yes	No	07:02	08:51	109
		3	07/05/2019	5	6	5.5	No	No	07:04	08:51	107
Five (July 2019)	One	1	21/07/2019	15	19	17	No	No	07:02	08:20	78
		2	22/07/2019	16	17	16.5	No	No	07:05	08:28	83
		3	23/07/2019	16	18	17	No	No	07:00	08:18	78
	Two	1	24/07/2019	16	17	16.5	No	No	07:00	08:32	92
		2	25/07/2019	16	17	16.5	No	No	07:00	08:36	96
		3	26/07/2019	16	18	17	No	No	07:02	08:44	102
	Three	1	27/07/2019	14	17	15.5	No	No	07:01	08:38	97
		2	28/07/2019	20	21	20.5	No	No	07:00	08:27	87
		3	29/07/2019	19	23	21	No	No	07:00	08:35	95
	Four	1	30/07/2019	18	19	18.5	No	No	07:03	08:32	89
		2	31/07/2019	18	19	18.5	No	No	07:00	08:26	86
		3	01/08/2019	16	18	17	No	No	07:07	08:33	86

***** Primary sampling period three, secondary sampling period two was missed due to fieldworker illness

Figure *S1. Examples of distinctiveness ratings of dogs identified across primary sampling periods: A1-3 of distinctiveness 1 (distinct with unique markings); B1-3 of distinctiveness 2 (moderately distinct, with some identifiable colouring/markings); and C1-3 of distinctiveness 3 (indistinct, mono-coloured, minimal markings).*

3. Details of hierarchical Bayesian hidden Markov model of Pollock's robust design

It is challenging to estimate demographic parameters using mark-recapture data because several ecological processes can lead to the mark-recapture histories that are observed. For example, individuals may be present in the population, but not detected during surveys, meaning their presence or absence is not an accurate estimate of whether an individual is contributing to the population processes. To deal with these challenges, a hierarchical Bayesian hidden Markov model of Pollock's closed robust design was used to analyse the mark-recapture histories for both Pescara and Lviv. Hidden Markov models deal with these challenges as they allow the underlying latent states of dogs (e.g. their presence or absence in the population) to be estimated depending on observations during the mark-recapture surveys (i.e. their capture histories).

Parameter-expansion and data augmentation:

Parameter-expansion and data augmentation simply involved adding a list of all-zero capture histories to the data to account for individuals that were never observed over the duration of the mark-recapture study. This allowed the states of both the individuals that were observed and those that were unobserved throughout the study (i.e. those that had very low detection probabilities) to be modelled, allowing better inferences to be made about the true population (Kery & Schaub, 2011; Rankin et al., 2016; Royle & Dorazio, 2008).

Specifically, parameter expanded data-augmentation deals with the computational challenges of variable dimension space when modelling full-capture histories and random effects for individual dogs (Kery & Schaub, 2011; Rankin et al., 2016; Royle & Dorazio, 2012; Tanner & Wong, 1987). In this study, a set of *pseudo-individuals* with all-zero (*unobserved*) capture histories were included in the list of capture histories for each of the study sites. The augmented dataset (m) totalled 150 individuals at each primary period in Pescara and 300 individuals at each primary period in Lviv. The augmented dataset (m) included the observed number of individuals (n) plus a number of *pseudo-individuals*, and the estimated number of individuals (N) lies between n and m. The *pseudo-individuals* did not affect the estimates of detection probability (δ), apparent survival (φ) or population size (N) but allowed more accurate estimation of the parameters using simpler computation. To test that the dataset included enough *pseudo-individuals*, the posterior distributions of N were plotted to ensure the distribution was not truncated to the right (Figures 2-6. The uncaptured *pseudo-individuals* made up the population of individuals that were available for recruitment into the study population and allowed modelling of individual random effects for dogs that were missed throughout all secondary sampling periods.

3.1. Entry probability

This provided the fraction of the true population ('super-population'; total number of dogs that had ever been in the study site across all primary periods) of individuals entering the study site at time t, given they had not entered at a previous time point. The entry probability must sum to one across all primary sampling periods and individuals were assumed to be in the *not yet entered* state prior to the first primary period. This means the entry probability calculated for the first primary period was less interpretable; instead, entry probabilities after the first primary period were reported. We also estimated a per capita entry probability (f), as described by Kery and Schaub (2011). Per capita entry probability describes the fraction of new recruits at primary period t per individual dog alive and in the study site at primary period t. This was calculated by Equation 1. Population growth (l_t) was calculated by dividing the estimated population size at period t (N_t) by the estimated population size at primary period N_{t-1} (Equation 2). Table S5 outlines the parameters calculated for each study site.

Equation 1. Per capita entry probability.

$$f_t = \frac{E_t \times W}{N_t}$$

Equation 2. Population growth

$$\lambda_t = \frac{N_t}{N_{t-1}}$$

Table S5. Description of parameters calculated for each study site in study regions.

Parameter	Description
$Z^{(m \times t)}$	Matrix of the possible latent states (*not-yet-entered; alive; dead*) for each individual (including *pseudo-individuals*) at each t primary sampling period.

Parameter	Description
n	Total number of dogs individually identified throughout the duration of the study.
N_t	Total number of dogs alive and available for observation during primary sampling period *t*.
m	Total number of dogs, including observed and unobserved *pseudo-individuals*.
$\gamma^{(m \times t \times s)}$	Array of capture histories for all individually identified dogs and the parameter expanded data augmented *pseudo-individuals*.
$\gamma^{(i \times t \times s)}$	Array of capture histories for all individuals *observed* in *s* secondary sampling periods throughout *t* primary sampling periods.
W	Superpopulation: Total number of dogs that have ever been in the study site across all primary sampling periods.
φ_{ti}	Apparent survival of individual dog between *t* and t^{+1} primary sampling period.
δ_{ti}	Probability of observing a dog, given it is alive, in secondary sampling period *s* within primary sampling period *t*.
ψ_{ti}	Probability of recruitment – an individual dog transitioning from *not yet entered* at t^{-1} to *alive* at *t* primary sampling period. As described, this is a nuisance parameter that is required to describe the model.
E_{ti}	Proportion of superpopulation entering at each primary period *t*, given they have not already entered.
f_t	Per capita entry probability: the fraction of new recruits at primary period *t* per individual dog alive and in the study site at primary period *t*.
λ	Population growth (Equation 2).
M_t	Matrix of time intervals between each primary sampling period.
M_d	Matrix of distances between study sites.

3.2. Model running

Data from study sites in Pescara and Lviv were run in the same model, but parameter estimates were not informed by capture histories between countries (i.e. parameter estimates for study sites in Pescara were not informed by those estimated for study sites in Lviv).

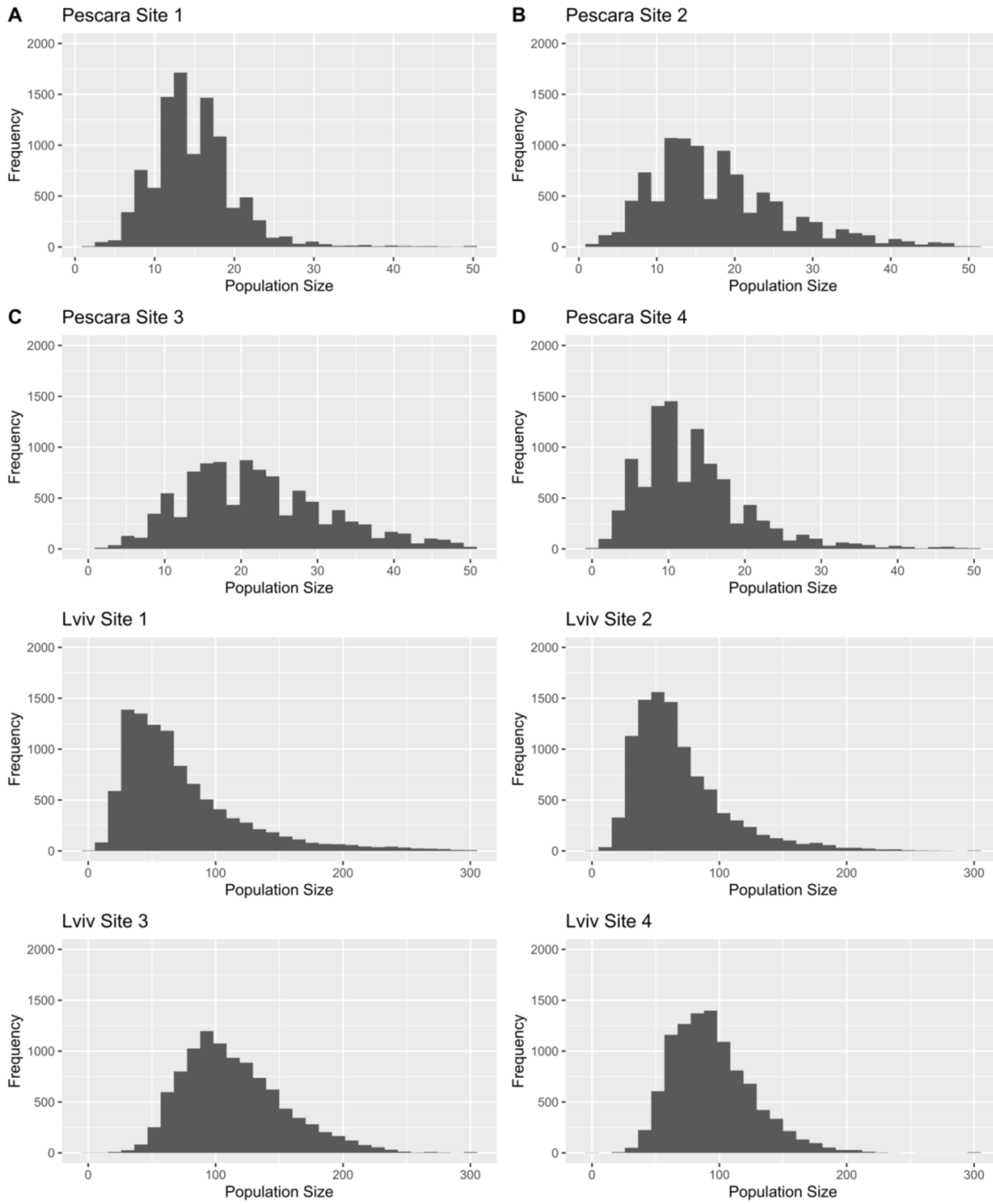

Figure S2. Posterior distribution of estimated population size (N) at primary sampling period 1 in study sites in Pescara and Lviv.

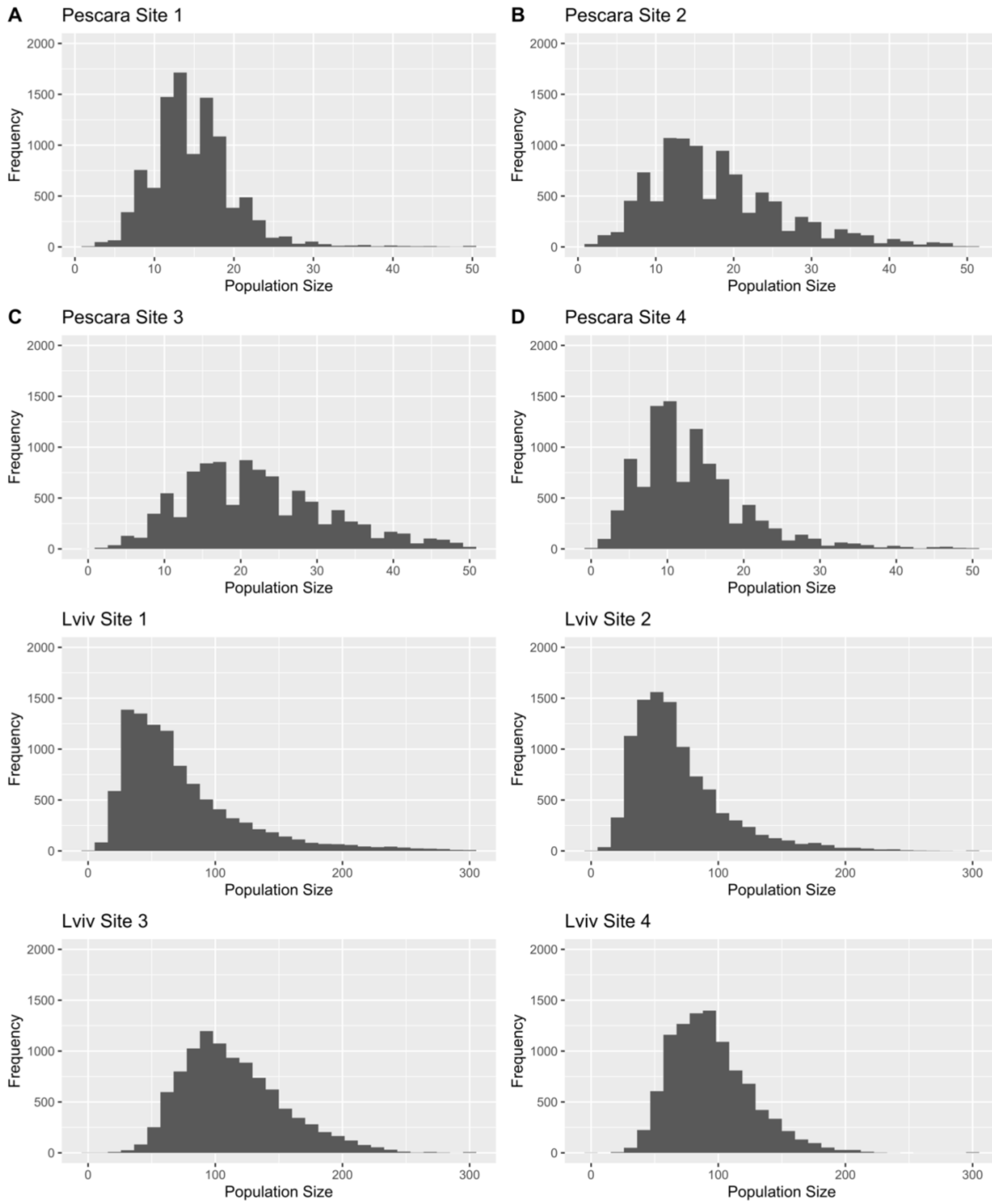

Figure S3. Posterior distribution of estimated population size (N) at primary sampling period 2 in study sites in Pescara and Lviv.

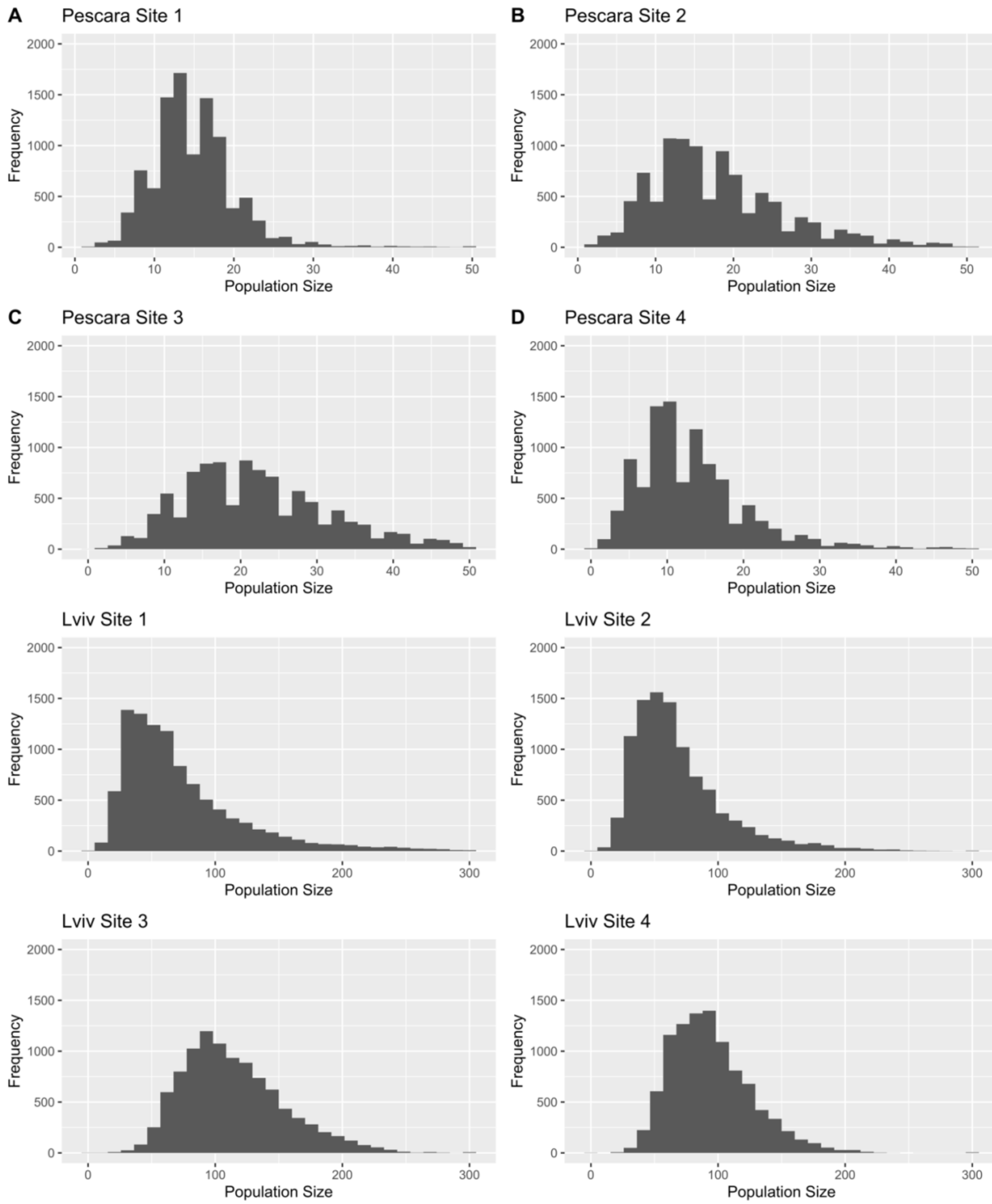

Figure S4. Posterior distribution of estimated population size (N) at primary sampling period 3 in study sites in Pescara and Lviv.

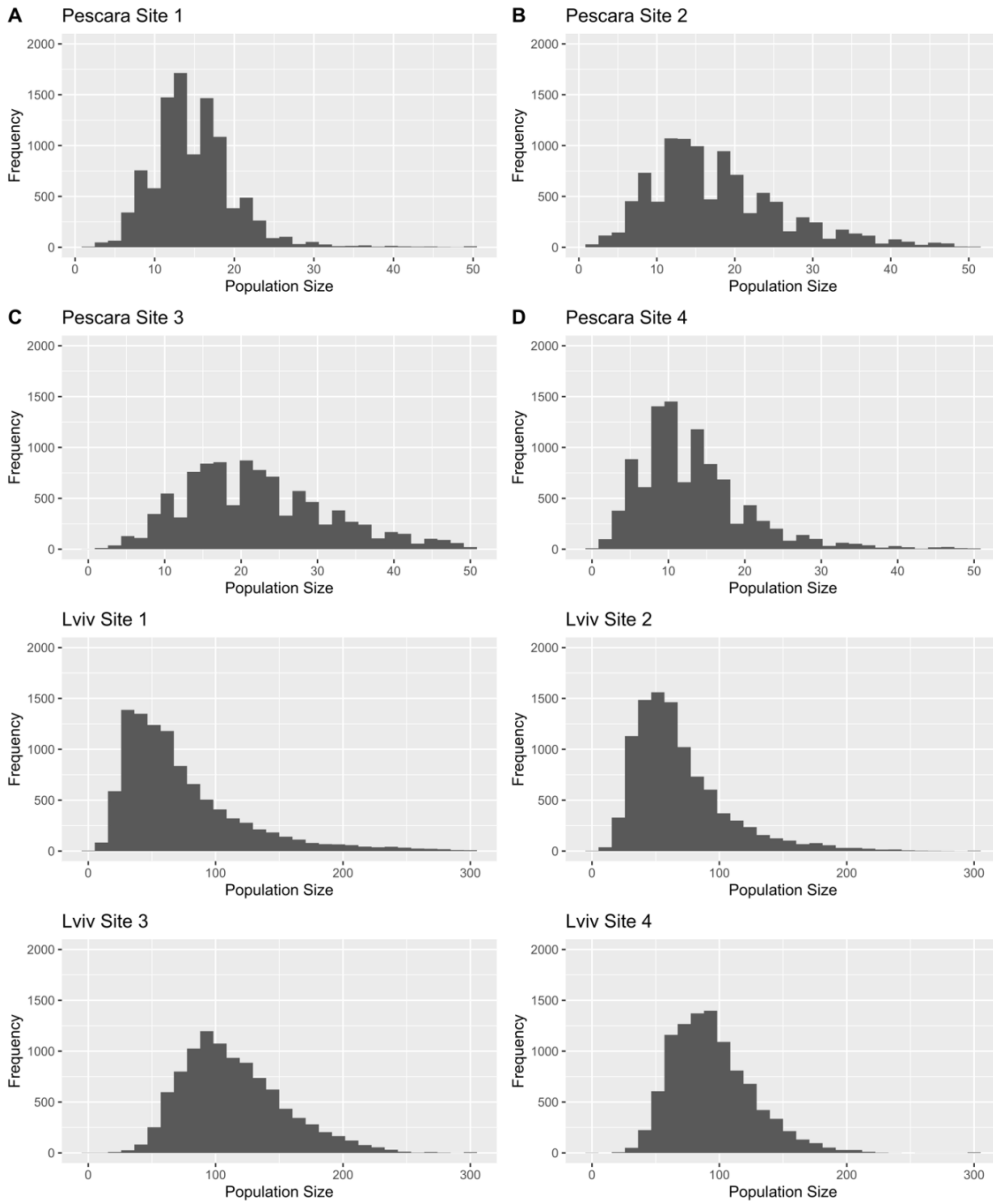

Figure S5. Posterior distribution of estimated population size (N) at primary sampling period 4 in study sites in Pescara and Lviv.

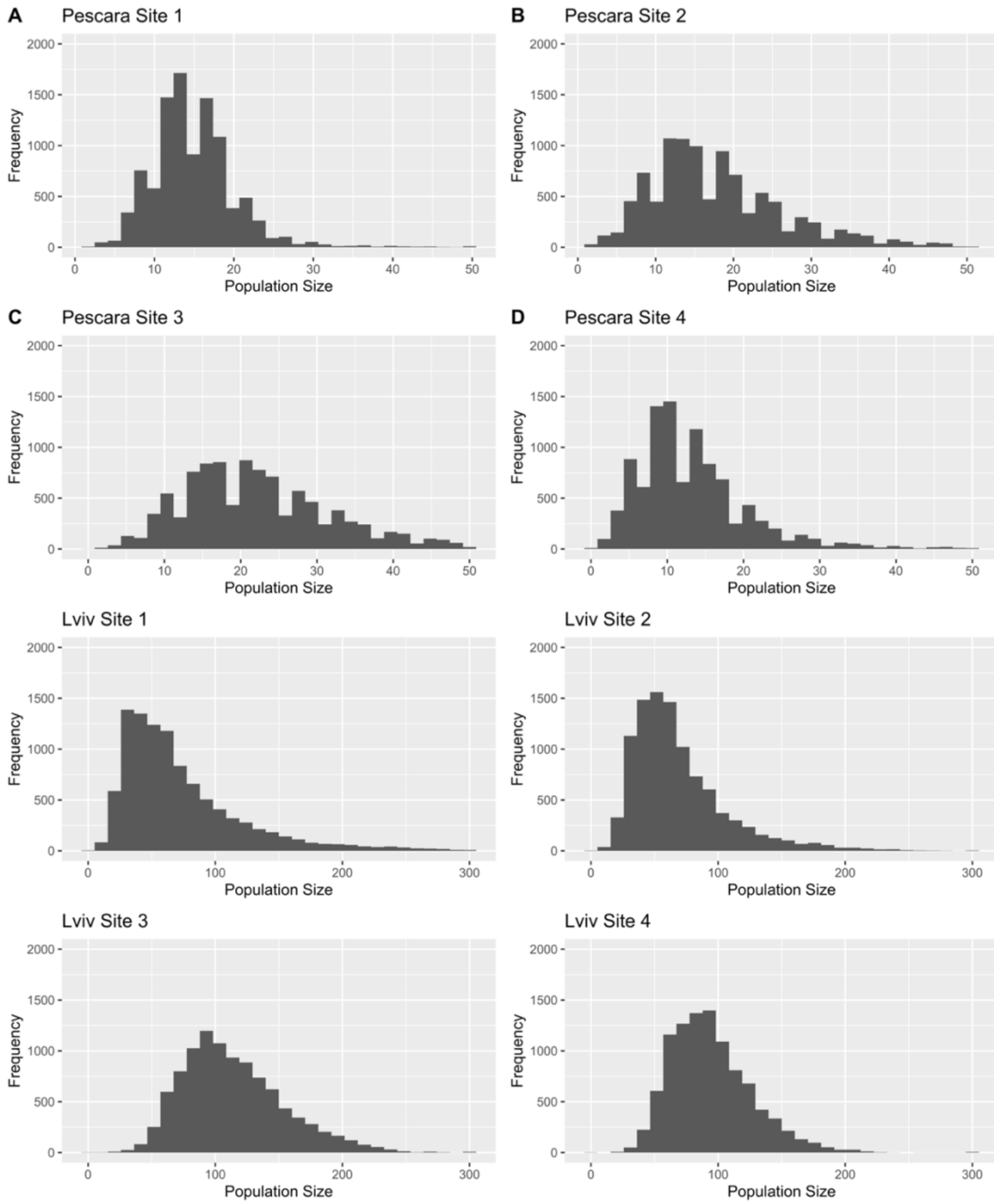

Figure S6. Posterior distribution of estimated population size (N) at primary sampling period 5 in study sites in Pescara and Lviv.

4. Results

In total, five primary sampling periods were completed in both Pescara and Lviv. Fifteen secondary sampling periods were completed in study sites in Pescara, and 14 secondary sampling periods were completed in Lviv between April 2018 and July 2019. No surveys were terminated due to conditions that may have shown abnormal free-roaming dog numbers. One survey (one secondary sampling period) did not occur due to fieldworker illness in study site one in Lviv during primary sampling period three.

Table S6. Probability of apparent survival and detection for primary sampling periods (averaged across individuals and study sites) and study sites (averaged across individuals and primary periods) in Pescara, Italy.

		Mean	**2.5% CI**	**97.5% CI**
Average probability of apparent survival	Primary Period 1 to 2 (3-month interval)	0.82	0.58	1.00
	Primary Period 2 to 3 (3-month interval)	0.74	0.44	0.99
	Primary Period 3 to 4 (6-month interval)	0.74	0.43	1.00
	Primary Period 4 to 5 (3-month interval)	0.79	0.47	1.00
	study site 1	0.77	0.48	0.98
	study site 2	0.71	0.36	0.99
	study site 3	0.71	0.33	1.00
	study site 4	0.77	0.45	1.00
Average probability of detecting a dog	Primary Period 1	0.23	0.04	0.47
	Primary Period 2	0.18	0.02	0.40
	Primary Period 3	0.20	0.03	0.42
	Primary Period 4	0.18	0.02	0.40
	Primary Period 5	0.25	0.04	0.52
	study site 1	0.41	0.14	0.74
	study site 2	0.18	0.01	0.46
	study site 3	0.11	0.01	0.27
	study site 4	0.22	0.01	0.51

Table S7. Probability of apparent survival and detection for primary sampling periods (averaged across individuals and study sites) and study sites (averaged across individuals and primary periods) in Lviv, Ukraine.

		Mean	**2.5% CI**	**97.5% CI**
Average probability of apparent survival	Primary Period 1 to 2 (3-month interval)	0.83	0.61	1.00
	Primary Period 2 to 3(3-month interval)	0.76	0.50	0.97
	Primary Period 3 to 4 (6-month interval)	0.90	0.73	1.00
	Primary Period 4 to 5(3-month interval)	0.73	0.44	0.97
	study site 1	0.83	0.56	1.00
	study site 2	0.82	0.57	1.00
	study site 3	0.75	0.46	0.98
	study site 4	0.67	0.35	0.93
Average probability of detecting a dog	Primary Period 1	0.08	0.00	0.21
	Primary Period 2	0.12	0.01	0.30
	Primary Period 3	0.14	0.01	0.34
	Primary Period 4	0.10	0.01	0.26
	Primary Period 5	0.10	0.01	0.25
	study site 1	0.07	0.00	0.22
	study site 2	0.11	0.00	0.31
	study site 3	0.10	0.00	0.28
	study site 4	0.16	0.01	0.41

Table S8. Standard deviations for between-dog effects on survival and detection on log odds scale.

		Pescara			**Lviv**		
	Study site	**Mean**	**2.5% CI**	**97.5% CI**	**Mean**	**2.5% CI**	**97.5% CI**
Survival (φ)	1	0.95	0.00	2.14	1.02	0.00	2.31
	2	1.01	0.00	2.30	0.77	0.00	1.87
	3	0.85	0.00	2.06	1.22	0.00	2.47
	4	0.78	0.00	1.92	0.63	0.00	1.54
Detection (δ)	1	0.55	0.00	1.37	1.58	0.81	2.34
	2	1.47	0.45	2.44	1.54	0.81	2.31
	3	0.48	0.00	1.17	1.85	1.20	2.49
	4	1.05	0.04	2.00	1.67	1.01	2.31

Table S9. Comparison of mean apparent survival and detection as odds ratios between different study sites in Pescara, Italy and Lviv, Ukraine.

		Pescara			Lviv		
Average probability	Study sites	Mean	2.5% CI	97.5% CI	Mean	2.5% CI	97.5% CI
Apparent survival (φ)	1 and 2	2.19	0.01	6.50	2.11	0.02	6.52
	1 and 3	2.62	0.01	7.97	3.41	0.06	10.76
	1 and 4	1.44	0.01	4.06	5.69	0.12	17.36
	2 and 3	2.08	0.00	6.79	2.56	0.07	6.98
	2 and 4	1.31	0.00	3.95	4.20	0.33	11.21
	3 and 4	1.54	0.00	4.77	2.08	0.23	4.89
Detection (δ)	1 and 2	6.68	0.18	20.69	0.87	0.01	2.76
	1 and 3	9.26	0.55	21.59	0.92	0.01	2.88
	1 and 4	4.57	0.14	14.13	0.48	0.01	1.47
	2 and 3	2.72	0.05	8.40	1.65	0.03	4.94
	2 and 4	1.30	0.01	4.38	0.84	0.01	2.34
	3 and 4	0.65	0.03	2.05	0.71	0.05	1.85

Table S10. Comparison of mean apparent survival and detection as odds ratios between different intervals between primary periods in Pescara, Italy and Lviv, Ukraine.

		Pescara			Lviv		
Average probability	Primary period	Mean	2.5% CI	97.5% CI	Mean	2.5% CI	97.5% CI
Apparent survival (φ)	2 to 3	4.06	0.01	11.64	2.56	0.14	6.82
	2 to 4	3.75	0.01	11.50	0.80	0.01	2.11
	2 to 5	3.12	0.00	8.37	3.05	0.07	8.38
	3 to 4	1.88	0.00	5.51	0.42	0.00	1.19
	3 to 5	1.33	0.00	4.16	1.54	0.09	4.00
	4 to 5	1.49	0.00	4.36	7.81	0.16	24.16
Detection (δ)	1 to 2	1.70	0.31	3.71	0.65	0.29	1.07
	1 to 3	1.29	0.46	2.37	0.59	0.19	1.10
	1 to 4	1.59	0.47	3.09	0.80	0.31	1.39
	1 to 5	1.10	0.20	2.40	0.87	0.31	1.56
	2 to 3	0.93	0.21	1.89	0.96	0.28	1.79
	2 to 4	1.26	0.11	3.13	1.31	0.53	2.28
	2 to 5	0.71	0.23	1.34	1.38	0.66	2.27
	3 to 4	1.33	0.41	2.50	1.45	0.80	2.26
	3 to 5	0.89	0.20	1.76	1.66	0.50	3.19
	4 to 5	0.79	0.09	1.78	1.14	0.45	1.96

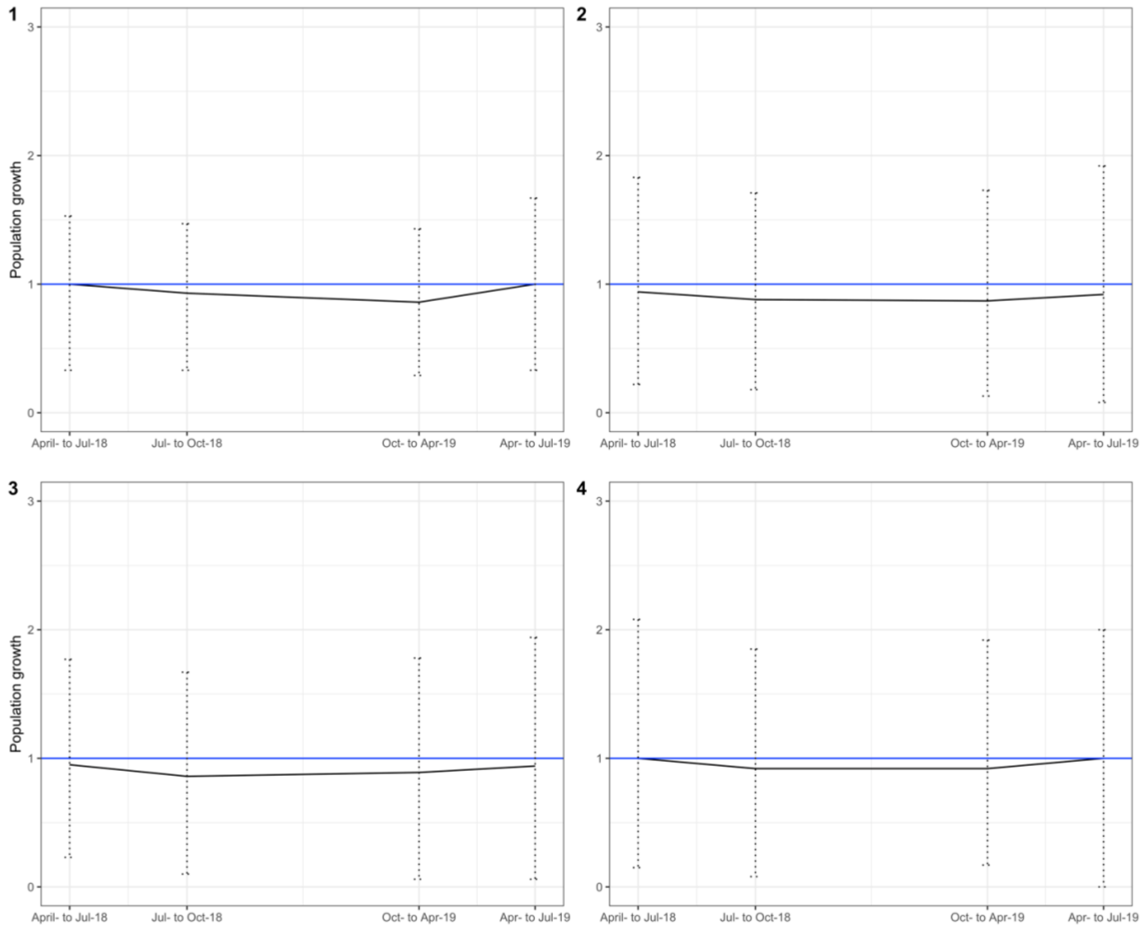

Figure S7. Population growth rates between primary sampling periods in study sites 1 to 4 for study regions Pescara, Italy. Error bars show the 2.5 and 97.5 percentiles of the posterior distribution (95% CI). Blue lines indicate stable population (i.e. no growth or decline). *Note uneven spacing as no surveys conducted in January 2019.

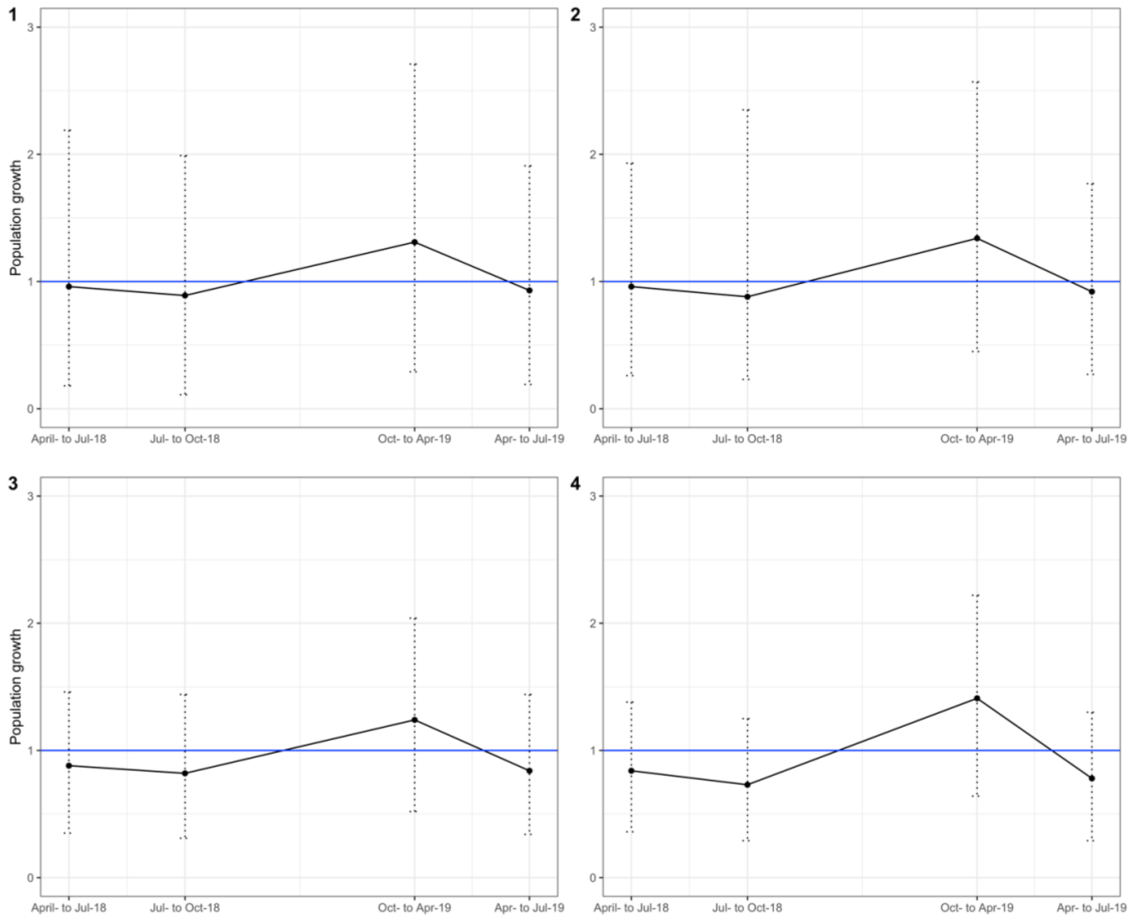

Figure S8. Population growth rates between primary sampling periods in study sites 1 to 4 for study regions Lviv, Ukraine. Error bars show the 2.5 and 97.5 percentiles of the posterior distribution (95% CI). Blue lines indicate stable population (i.e. no growth or decline).* Note uneven spacing as no surveys conducted in January 2019.

References

Istituto Nazionale di Statistica. (n.d.). Retrieved February 12, 2020, from https://www.istat.it/en/

Kery, M., & Schaub, M. (2011). Estimation of Survival, Recruitment, and Population Size from Capture-Recapture Data Using the Jolly-Seber Model. In *Bayesian Population Analysis using WinBUGS: A Hierarchical Perspective* (First, pp. 316–346). Waltham: Elsevier Inc.

Peel, M. C., Finlayson, B. L., & Mcmahon, T. A. (2007). Updated world map of the Köppen-Geiger climate classification. *Hydrology and Earth System Sciences Discussions*, *4*(2), 439–473.

Rankin, R. W., Nicholson, K. E., Allen, S. J., Krützen, M., Bejder, L., & Pollock, K. H. (2016). A Full-Capture Hierarchical Bayesian Model of Pollock's Closed Robust Design and Application to Dolphins. *Frontiers in Marine Science*, *3*(25), 1–18. doi: 10.3389/fmars.2016.00025

Royle, J. A., & Dorazio, R. M. (2008). Modeling Population Dynamics. In A. J. Royle & R. M. Dozario (Eds.), *Hierarchical Modeling and Inference in Ecology: The analysis of data from populations, metapopulations and communities* (First, pp. 325–345). San Diego, United States: Elsevier Science Publishing Co Inc. doi: 10.1016/b978-0-12-374097-7.00012-0

Royle, J. A., & Dorazio, R. M. (2012). Parameter-expanded data augmentation for Bayesian analysis of capture-recapture models. *Journal of Ornithology*, *152*(SUPPL. 2), 521–537. doi: https://doi.org/10.1007/s10336-010-0619-4

State Statistics Service of Ukraine. (n.d.). Population of Ukraine. Retrieved October 18, 2017, from http://database.ukrcensus.gov.ua/MULT/Quicktables/KEY_IND/key_index.asp

State Statistics Service of Ukraine. (2018). *ДЕРЖАВНА СЛУЖБА СТАТИСТИКИ УКРАЇНИ STATE STATISTICS SERVICE OF UKRAINE*. Kyiv, Ukraine.

Tanner, M. A., & Wong, W. H. (1987). The calculation of posterior distributions by data augmentation. *Journal of the American Statistical Association*, *82*(398), 528–540. doi: 10.1080/01621459.1987.10478458